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Effects of Satellite Spectral Resolution and Atmospheric Water Vapor on Retrieval of Near-ground Temperatures

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ABSTRACT

The vertical resolution capabilities of the VISSR Atmospheric Sounder (VAS) and the proposed GOES High-resolution Interferometer Sounder (GHIS) were considered with regard to temperatures at and near the ground surface. Simulated retrievals were performed, along with experiments on the sensitivity of radiances to profile perturbations. For a moderately moist atmosphere, ground surface temperature errors of about 1°C and low-level air temperature errors of about 3°C can occur in VAS retrievals due specifically to vertical resolution limitations and instrument noise. For a drier atmosphere the surface temperature errors tend to be smaller and the low-level air temperature errors tend to be larger. It appears that these vertical-resolution-related retrieval errors can be reduced by a factor of about 70-90% by going from VAS to an instrument with performance specifications such as those of GHIS. These results also imply that a high-spectral-resolution instrument can perform significantly better than VAS in the task of estimating cloud top heights and temperatures for low clouds.

1. INTRODUCTION

Ground surface temperatures play a large role in determining surface energy fluxes by way of their effects on sensible, latent, and radiative energy transfer. It is therefore necessary to estimate surface temperatures when studying atmospheric processes that depend heavily on surface fluxes. Mesoscale short-range forecasts and climatological analyses can be particularly reliant on surface temperature estimation.

Widespread and frequent measurements of ground surface temperature can be made using satellite-based infrared sounders. The primary drawback of this method is that the accuracy of surface temperature retrievals is sensitive to cloud cover, and they cannot be made at all under overcast conditions. Errors in the assumed surface emittance can be another significant source of retrieval error.^{1,2,3} Nevertheless, satellite-retrieved surface temperatures can be very useful for mesoscale analysis when cloud cover is incomplete. For example, surface temperature information from the VISSR Atmospheric Sounder (VAS) has been used by Lipton and Vonder Haar⁴ in four-dimensional numerical analysis of circulations in the northeastern Colorado region, using an analysis system that consists of retrieval algorithms coupled with a mesoscale numerical model.

One of the challenges in remote sensing of surface temperatures is to distinguish clearly the influence of the ground surface on the measured radiances from the influence of the overlaying atmosphere. It is common, particularly in cloud-free situations, to have large differences in temperature over very short vertical distances from the ground up through the lowest kilometer of the atmosphere. The research reported here focused on the vertical resolution capabilities of satellite sounders in this lowest part of the temperature profile, with an orientation toward mesoscale analysis applications.

The meteorological conditions considered were representative of a midlatitude, summertime, potentially convective environment (Fig. 1). The two temperature profiles that were used differed only in their low-level air and ground surface temperatures. One was characteristic of nighttime conditions, just before dawn, with a strong surface-based temperature inversion. The other was characteristic of midday conditions in the presence of strong solar heating of the ground. For radiative transfer calculations it was assumed that there was a temperature discontinuity between the bottom of the atmosphere and the ground surface, instead of

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The results of the retrieval and sensitivity experiments were more varied with regard to GHIS, stemming from the experiments' different assumptions about channel-to-channel correlations of data noise. Nevertheless, it appears that these vertical-resolution-related retrieval errors can be reduced by a factor of about 70-90% by going from VAS to an instrument with performance specifications such as those of GHIS. These results also imply that a high spectral resolution instrument can perform significantly better than VAS in the task of estimating cloud top heights and temperatures for low clouds.

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trying to model the actual gradient of temperature between the ground and the ~2-m height at which "surface" air temperature observations are typically made. The specified temperature differences between the ground surface and the bottom of the atmosphere were appropriate for these meteorological conditions^{6,6} (although plotting ground surface temperatures on a skew- T /log- p diagram makes them appear to be extreme).

Midlatitude summer situations typically have water vapor concentrations somewhat less than in the tropics, but considerably greater than in cooler seasons and latitudes. Given the large effect of water vapor on infrared radiative transfer in the lower troposphere, an alternate low-level water vapor profile was considered. This "dry" water vapor profile (dashed in Fig. 1) was specified to be equal to the "basic" midlatitude summer profile (solid in Fig. 1) except that its dew-point temperature was linear (in log-pressure) from the value at 700 mb to a value of 0°C at the surface. The dry profile had about half as much integrated precipitable water as the basic profile—14 mm versus 27 mm.

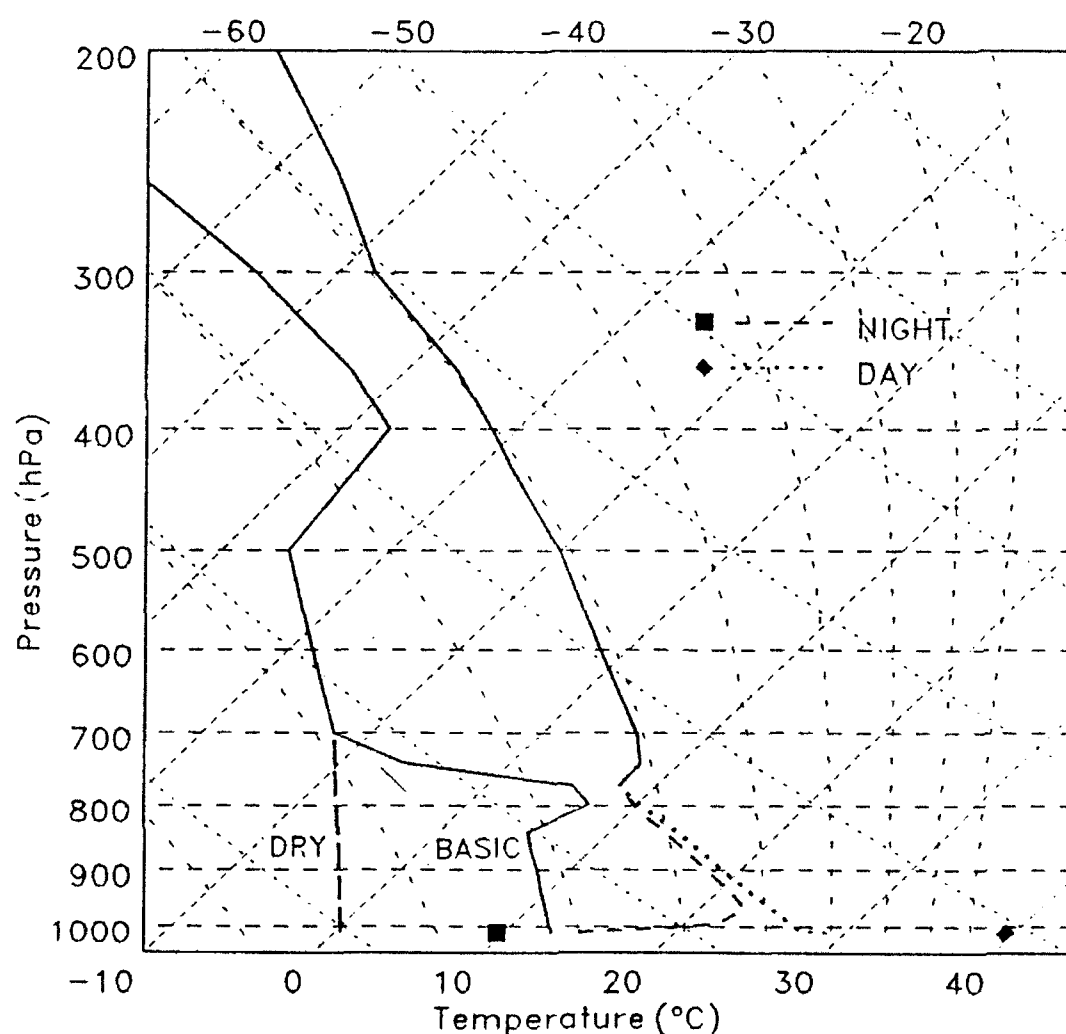


Figure 1. The reference temperature (right curves) and dewpoint temperature (left curves) profiles, with marker symbols indicating ground surface temperatures. The two versions of the bottom portion of the temperature curve correspond to the night and day reference conditions. The solid and dashed versions of the bottom of the dewpoint temperature curve correspond to the basic and dry profiles, respectively.

2. SATELLITE INSTRUMENTS

Only geostationary satellite sounders were considered in these experiments because they can provide the frequent observations needed for mesoscale analysis. The VAS filter radiometer is such a sounder, and is currently operating on a Geostationary Operational Environmental Satellite (GOES) platform. The capabilities of the VAS, which has relatively low spectral resolution,⁷ were compared with a proposed instrument, the GOES High-resolution Interferometer Sounder (GHIS).⁸ While there is no assurance that the particular design of the GHIS will ever be implemented on GOES, the performance specifications Smith *et al.*⁸ provided are taken as representative of high-spectral-resolution sounder technology.

The satellite data for both the operational and proposed instruments were simulated, so that the instruments could be compared on an equivalent basis. Use of simulations also made it possible to treat the vertical resolution issue in isolation from the other potential sources of retrieval error. Simulated radiances for VAS were computed with MODTRAN software,⁹ while for GHIS simulations it was necessary to use the higher-resolution, but computationally slower, FASCODE-3.¹⁰

Both VAS and GHIS have surface-sensitive channels in both the 10–14- μm band and the 3–5- μm band, but only the former band was considered here because it is free of the effects of solar radiation. Another advantage of the 10–14- μm band is that variations of surface emittance from unity tend to be smaller than in the 3–5- μm band^{2,11} nevertheless, such variations were not considered in these experiments. The instrument noise standard deviations for the channels in the 10–14- μm band are listed in Table 1 in terms of radiance. Noise values for VAS were based on the typical spin budgets used in dwell sounding mode (Table 1), where the spin budget represents the number of observations taken for a given field of view and the noise values have been reduced from single-observation values by a factor of the square root of the spin budget.

Table 1. Noise levels of sounding instruments.

VAS ¹²			GHIS ⁸		
Channel	Spin budget	Noise standard deviation $\left(\frac{\times 10^{-7} \text{ W}}{\text{cm}^2 \text{ sr cm}^{-1}} \right)$	Mode	Spectral resolution (cm^{-1})	Noise standard deviation $\left(\frac{\times 10^{-7} \text{ W}}{\text{cm}^2 \text{ sr cm}^{-1}} \right)$
5	2	0.5	low	3.33	0.14
7	2	0.6	high	0.32	0.46
8	1	0.3			

The proposed GHIS has three spectral resolution modes: low, medium and high. Only the low and high-resolution modes were considered here, and will hereafter be referred to as GHIS(low) and GHIS(high), respectively. Even the low-resolution mode has much finer spectral resolution than VAS. The spectral resolving powers of VAS and GHIS are illustrated in Fig. 2. VAS spans nearly all of the wavenumber range 720–1010 cm^{-1} with just three channels (Fig. 2a). The plot of surface transmittance (Fig. 2b) illustrates the spectral detail available with GHIS(high). The ability of GHIS to observe between individual absorption lines results in a maximum computed surface transmittance of 0.78 (at 964 cm^{-1}) for the basic water vapor profile, whereas the maximum transmittance computed for VAS (in channel 8) was 0.63. Given that the atmospheric contribution to a radiance is indicated by one minus the transmittance, these transmittance values imply that there is a reduction in atmospheric contribution of ~40%, going from VAS to GHIS. Such a reduction can be expected to facilitate distinguishing the thermal signature of the ground surface from any atmospheric effects.

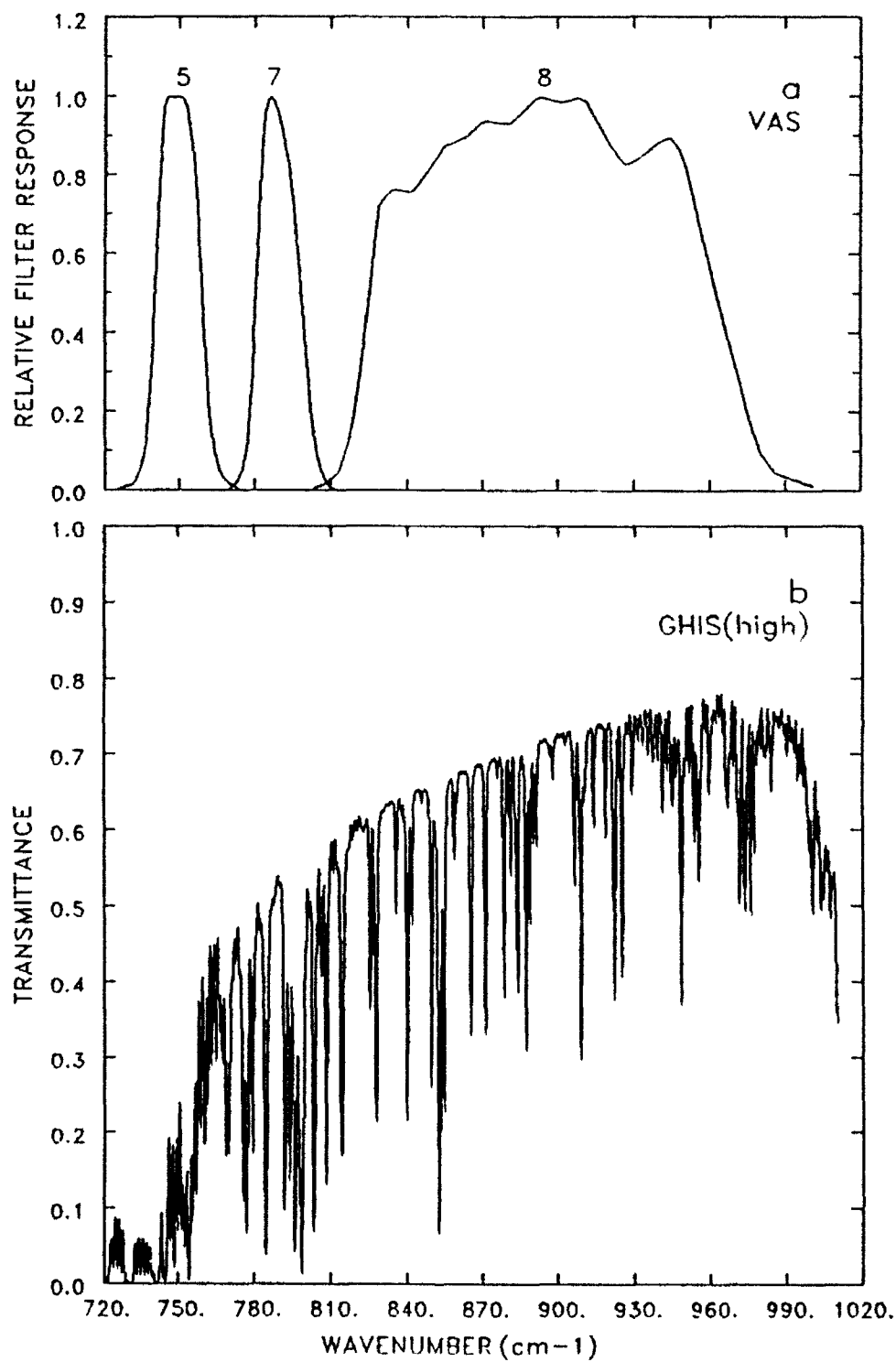


Figure 2. Relative filter response for VAS (a), and atmospheric transmittance from the ground to space for the night reference condition, with the basic water vapor profile, for GHIS(high) (b). The curves in (a) are labeled according to VAS channel number.

In comparison with the situation of the basic water vapor profile, GHIS and VAS both had a much clearer view of the surface for the dry conditions, with maximum transmittance values of 0.94 and 0.85, respectively. This result implies that both instruments would give more-accurate surface temperature retrievals under dry conditions than under moist ones.

3. SENSITIVITY EXPERIMENTS

The question of how well VAS and GHIS can resolve the ground surface versus the air just above was addressed by considering the changes in computed radiances caused by perturbing the reference temperature profiles of Fig. 1 in two specific ways. The first type of perturbation consisted of a change in the ground surface temperature ΔT_{sfc} . The second was a systematic change in the low-level air temperature, represented by the ratio f , such that

$$f = \frac{T_p(p) - T_o(p)}{T_r(p) - T_o(p)}, \quad (1)$$

where temperatures are given as functions of pressure, subscripts p and r indicate the perturbed and reference profiles, respectively, and T_o is a profile extending linearly (in $\log p$ coordinates) from the perturbed ground surface temperature to the base of the isothermal layer at 770 mb. These perturbations are illustrated for the night situation in Fig. 3. As examples, if $f = 0$ the warm layer just above the surface is completely destroyed ($T_p = T_o$), if $f = 1$ the air has the same temperature as with the reference profile, and if $f \geq 1$ the warm layer is enhanced.

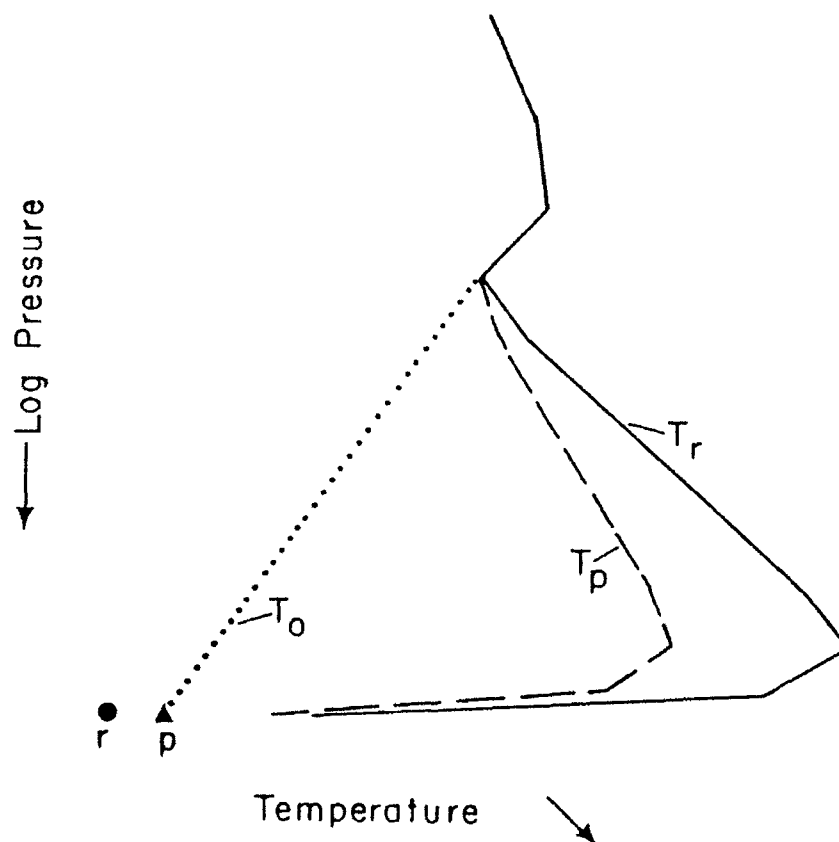


Figure 3. An illustration of the profile perturbation process, for the night situation. The dot and triangle indicate the reference and perturbed ground surface temperatures, respectively. The solid and dashed curves indicate the reference and perturbed temperature profiles, respectively.

The perturbations were defined in terms of these two specific free parameters (ΔT_{sfc} and f) to allow for representing the ambiguity that can occur when interpreting radiances from channels sensitive to the ground. Any increase in radiance caused by warming of the ground can be partly compensated for by a cooling of the air just above the ground, and vice versa. This particular definition of the perturbations also limits the results to profiles that are meteorologically realistic.

Experiments were conducted to determine how much these two free parameters could be perturbed without causing any computed radiances to differ from reference-profile radiances by more than one standard deviation of the instrument noise. The results can be viewed as indicating how much retrievals could differ from the true (reference) profile, in terms of compensating ground/air temperature errors, without exceeding the noise limit. The signs of the perturbations were arbitrarily chosen such that the ground surface would warm and the lower atmosphere would cool for the night situation, and the opposite would occur for the day situation.

Figure 4 is an illustration of how the sensitivity experiments were done for the night situation, with the basic water vapor profile and the high-resolution mode of GHIS. The radiance differences plotted correspond

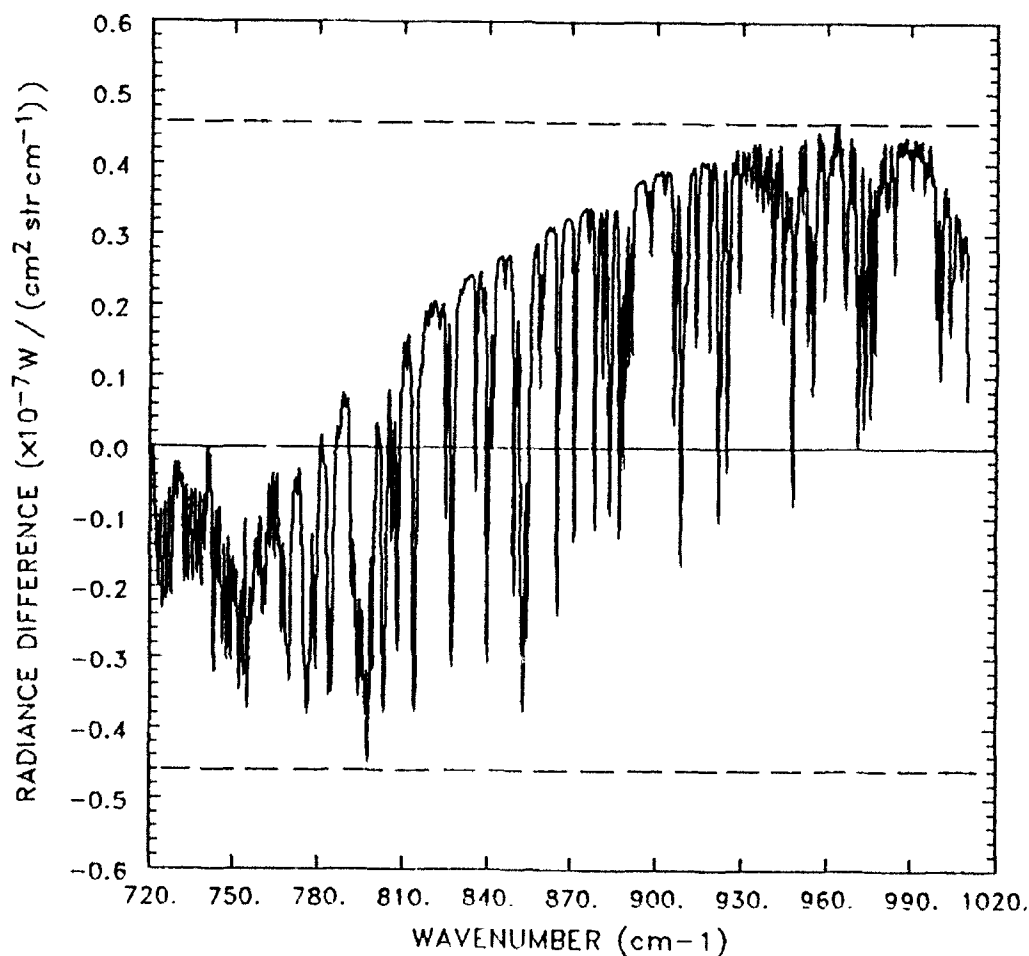


Figure 4. Difference in spectral radiance for GHIS(high) and the night basic situation—perturbed profile ($\Delta T_{sfc} = 0.60$, $f = 0.86$) minus reference profile. The dashed lines denote the noise level for GHIS(high).

to perturbation parameter values $\Delta T_{sf} = 0.60$ and $f = 0.86$. Differences are positive in spectral regions where the atmospheric transmittance is largest and are negative in regions where sensitivity is concentrated in the 800 to 950-mb layer. This is the noise-limited condition in the sense that the noise level (taken from Table 1) would be exceeded near 960 cm^{-1} if ΔT_{sf} were increased or near 800 cm^{-1} if f were decreased any further.

The noise-limited perturbations for VAS and GHIS, with the basic water vapor profile, are plotted in Fig. 5 and summarized in Table 2. The vertical resolution and noise characteristics of VAS are such that it allowed perturbations about twice as large as for GHIS(high) and about five times as large as for GHIS(low). Table 2 also includes results for the dry water vapor profile for the night situation. As expected, the unresolvable perturbations of surface temperature were smaller for the dry atmosphere than for the moist one. Furthermore, the relative advantage of GHIS over VAS with regard to surface temperature perturbations is smaller for a drier atmosphere, particularly for GHIS(high). This result is consistent with the smaller GHIS(high)-VAS difference in maximum transmittance ($0.94 - 0.85 = 0.09$ versus $0.78 - 0.63 = 0.15$) for the dry case as compared to the basic case. The unresolvable air temperature perturbations (rightmost column) became larger for the drier atmosphere, as would be expected when there is a weaker signal from the lower atmosphere in the radiances.

Table 2. Absolute differences of temperature between noise-limited perturbed and reference profiles.

Instrument	Ground surface temperature difference (°C)	Largest air temperature difference (°C)
Night (basic):		
VAS	1.2	3.5
GHIS(low)	0.2	0.7
GHIS(high)	0.6	1.4
Day (basic):		
VAS	1.0	2.8
GHIS(low)	0.2	0.6
GHIS(high)	0.5	1.6
Night (dry):		
VAS	0.5	4.0
GHIS(low)	0.1	0.9
GHIS(high)	0.4	1.9

GHIS(low) outperformed GHIS(high) in these experiments because its lower noise level more than compensated for its lower vertical resolving power. A limitation of these experiments, however, is that they do not account for the vast differences in the number of channels available with each of these instrument configurations. GHIS(low) has about 90 channels in the spectral band considered here, while GHIS(high) has about 900. Given a radiance error limit of one noise standard deviation, retrievals with errors as large as these perturbation-reference differences would occur only if observed radiances had the property that all channels most sensitive to the ground had errors of one sign and all channels most sensitive to the lower atmosphere had errors of the opposite sign. This represents a particular pattern of channel-to-channel error correlation that is very unlikely to ever be realized with 90 channels, and is even less likely with 900 channels. In contrast, such a correlation pattern is likely to be realized occasionally when there are just 3 channels, as VAS has in this band. Retrieval experiments were conducted to address this issue.

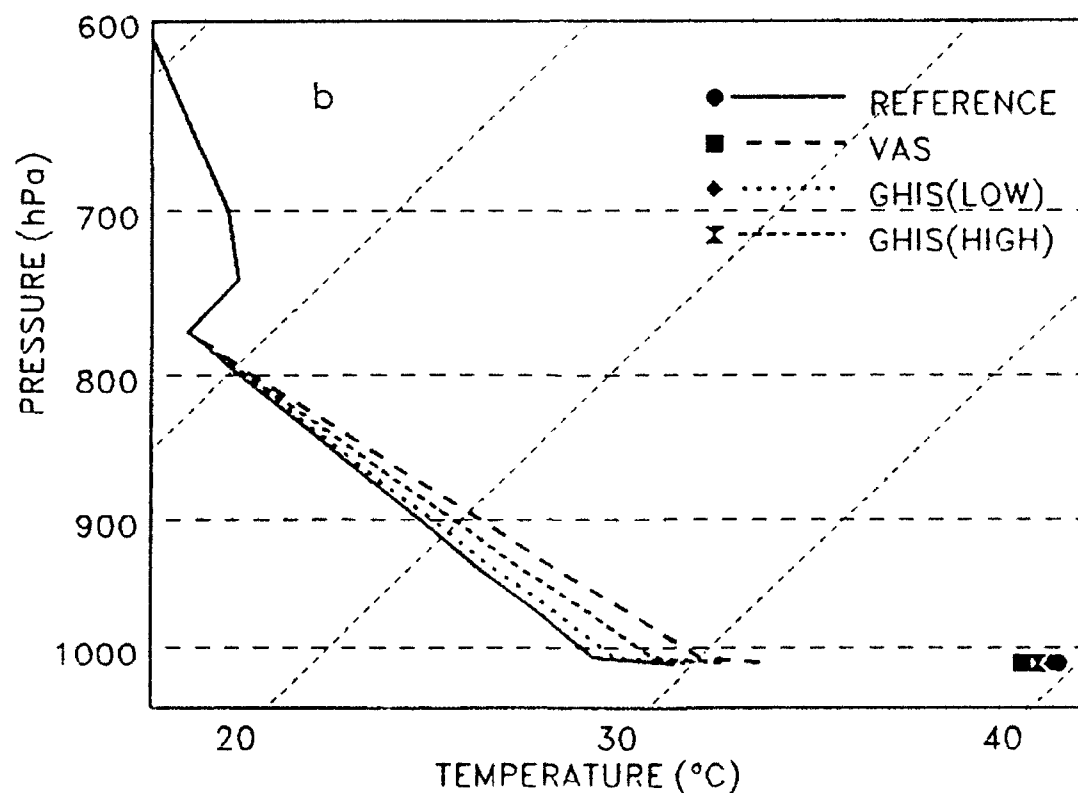
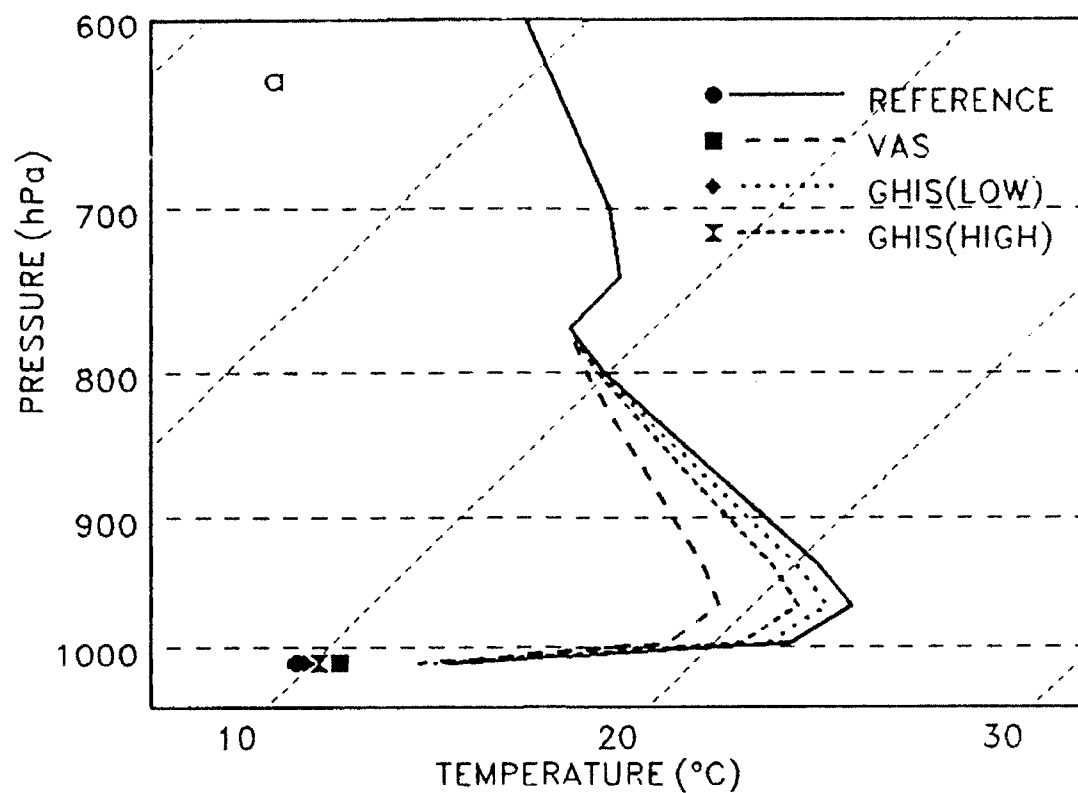


Figure 5. Noise-limited perturbed temperature profiles for the (a) night and (b) day situations with the basic water vapor profile, labeled according to satellite instrument. Marker symbols indicate ground surface temperatures, where the GHIS(low) and reference markers overlap.

4. RETRIEVAL EXPERIMENTS

Retrievals were performed only for the night reference situation with the basic water vapor profile, under the assumption that retrieval experiments for the day situation and for the dry profile would offer little information beyond what can be inferred from these results and those of the sensitivity experiments. The retrievals employed simulated radiances with pseudorandom noise added according to the standard deviations listed in Table 1. Ten retrievals were performed for each instrument configuration, each with a different set of radiances based on different noise realizations.

The retrieval formulation was chosen appropriately for this study's focus on resolvability of the ground. A non-linear, iterative, least-squares solution for the perturbation parameters was used, where

$$\mathbf{x}_{n+1} = \mathbf{x}_n + \left(\mathbf{K}_n^T \cdot \mathbf{E}^{-1} \cdot \mathbf{K}_n \right)^{-1} \cdot \mathbf{K}_n^T \cdot \mathbf{E}^{-1} \cdot \left\{ \mathbf{y}^m - \mathbf{y}(\mathbf{x}_n) \right\} \quad (2)$$

is the retrieval equation, the solution vector is

$$\mathbf{x} = \left[\begin{array}{c} \Delta T_{sfc} \\ f \end{array} \right], \quad (3)$$

n is the iteration number, \mathbf{y}^m is the vector of simulated measurement radiances, $\mathbf{y}(\mathbf{x})$ is the vector of computed radiances, \mathbf{E} is the measurement error covariance matrix, and \mathbf{K} is the matrix of partial derivatives of the elements of \mathbf{y} with respect to the elements of \mathbf{x} .^{13,14} The initial guess \mathbf{x}_0 was the night reference profile. The elements of \mathbf{K} were computed by the brute force method, which consists of computing radiances for a given \mathbf{x} , then with each of the two elements of \mathbf{x} altered by a small amount, and finally computing derivatives in terms of finite differences.

Note that this formulation does not include any constraint tying the solution to a background profile and, thus, the solution to which the profile parameters converge is dictated fully by the measured (simulated) radiances. In addition, the measurement errors were assumed to be completely uncorrelated, so \mathbf{E} is diagonal. Error variances for VAS were taken from the instrument noise statistics (Table 1). For GHIS the specified noise is the same for all channels in the relevant band and, therefore, \mathbf{E}^{-1} is just the product of a scalar and an identity matrix and can be eliminated from Eq. 2.

The worst-case results from among the ten noise realizations are plotted in Fig. 6 and summarized in Table 3. The retrieval-profile differences for VAS and GHIS(high) happened to have signs opposite from those of the sensitivity experiment differences (Fig. 5) but, for VAS, the magnitudes of the differences were very similar in the two sets of experiments. In contrast, the GHIS retrieval results were much closer to the reference profiles than were the GHIS sensitivity experiment results.

Another significant feature of the retrieval results is that GHIS(high) outperformed GHIS(low) by about a factor of two, demonstrating how the greater number of channels can offset the greater noise level in the high-resolution mode.

Table 3. Absolute differences of temperature between the worst of ten retrievals and the reference profile.

Instrument	Ground surface temperature difference (°C)	Largest air temperature difference (°C)
Night:		
VAS	1.01	3.68
GHIS(low)	0.11	0.40
GHIS(high)	0.05	0.23

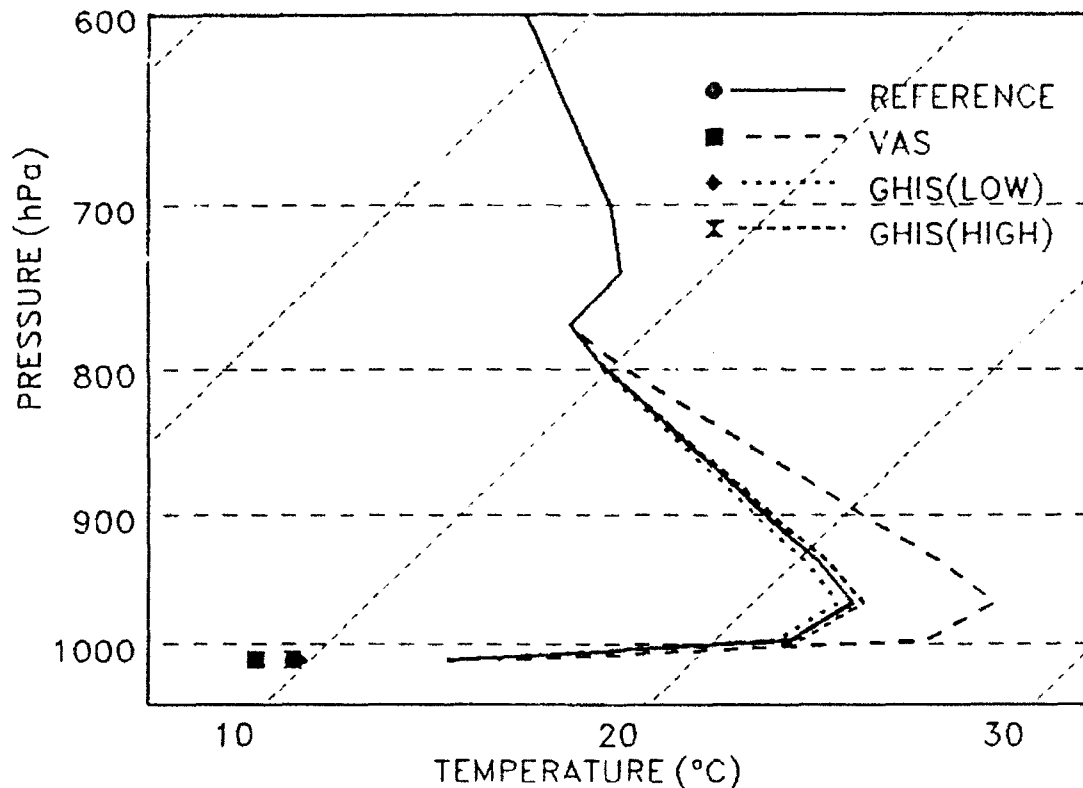


Figure 6. Retrieved temperature profiles (the worst of ten simulations) for the night situation with the basic water vapor profile, labeled according to satellite instrument. Marker symbols indicate ground surface temperatures, where the GHIS markers almost directly overlay the reference marker.

5. CONCLUSION

The results of simulated retrievals and experiments on the sensitivity of radiances to profile perturbations gave an indication of how well VAS and a proposed high-spectral-resolution sounder, GHIS, are able to resolve the ground surface from the air just above ground. Interpretation of the results must be constrained by the fact that only two water vapor profiles and two, midlatitude summertime, temperature profiles were considered.

The two sets of experimental results agreed that, for a moderately moist atmosphere, ground surface temperature errors of about 1°C and low-level air temperature errors of about 3°C can occur in VAS retrievals due specifically to vertical resolution limitations and instrument noise. For a drier atmosphere the surface temperature errors tend to be smaller and the low-level air temperature errors tend to be larger. These values do not account for other sources of retrieval error, such as interference by clouds, uncertainty of the ground surface emittance, or deficiencies in the radiative transfer computation method.

The results of the retrieval and sensitivity experiments were more varied with regard to GHIS, stemming from the experiments' different assumptions about channel-to-channel correlations of data noise. Nevertheless, it appears that these vertical-resolution-related retrieval errors can be reduced by a factor of about 70–90% by going from VAS to an instrument with performance specifications such as those of GHIS.

The results discussed above are relevant to retrieval of cloud top heights and temperatures, particularly for low clouds, where a major challenge is to distinguish the clouds' radiative signal from those of the overlaying atmosphere and the clouds' background. Vertical temperature gradients tend to be smaller above

cloud tops than above ground surfaces; with cloud retrievals, the greater concern is with the effects of incomplete cloud cover and non-unity emittances. High spectral resolution is helpful in addressing all of these effects.

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